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ISOSPIN AND MOMENTUM DEPENDENCE OF LIQUID-GAS PHASE TRANSITION IN HOT ASYMMETRIC NUCLEAR MATTER

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The liquid-gas phase transition in hot neutron-rich nuclear matter is investigated within a self-consistent thermal model using different interactions with or without isospin and/or momentum dependence. The boundary of the phase-coexistence region is shown to be sensitive to the density dependence of the nuclear symmetry energy as well as the isospin and momentum dependence of the nuclear interaction.

1. Introduction

The liquid-gas (LG) phase transition in nuclear matter remains illusive and a hot research topic despite of the great efforts devoted to understanding its nature and experimental manifestations by the nuclear physics community over many years^{1,2,3,4}. For a recent review, see, e.g., Refs.^{5,6,7}. Most of the previous studies have focused on the LG phase transition in symmetric nuclear matter. While in an asymmetric nuclear matter, the LG phase transition is expected to display some distinctly new features because of the isospin degree of freedom and the associated interactions and additional conservation laws⁸. This expectation together

with the need to understand better properties of asymmetric nuclear matter relevant for both nuclear physics and astrophysics have stimulated a lot of new work recently^{9,10,11,12,13,14,15,16,17,18,19,20,21}. Moreover, the study on the LG phase transition in asymmetric nuclear matter has received recently a strong boost from the impressive progress in developing more advanced radioactive beams that can be used to create transiently in terrestrial laboratories large volumes of highly asymmetric nuclear matter. Though significant progress has been made recently in studying properties of isospin asymmetric nuclear matter and the LG phase transition in it, there are still many challenging questions to be answered. Among the main difficulties are our poor understanding about the isovector nuclear interaction and the density dependence of the nuclear symmetry energy^{7,22,23}. Fortunately, recent analyses of the isospin diffusion data in heavy-ion reactions have allowed us to put a stringent constraint on the symmetry energy of neutron-rich matter at sub-normal densities^{24,25,26}. It is therefore interesting to investigate how the constrained symmetry energy may allow us to better understand the LG phase transition in asymmetric nuclear matter. Moreover, both the isovector (i.e., the nuclear symmetry potential) and isoscalar parts of the single nucleon potential should be momentum dependent. However, effects of the momentum-dependent interactions on the LG phase transition in asymmetric nuclear matter were not thoroughly investigated previously.

We report here our recent progress in investigating effects of the isospin and momentum dependent interactions on the LG phase transition in hot neutron-rich nuclear matter within a self-consistent thermal model using three different interactions²⁷. The first one is the isospin and momentum dependent MDI interaction constrained by the isospin diffusion data in heavy-ion collisions. The second one is a momentum-independent interaction (MID) which leads to a fully momentum independent single nucleon potential, and the third one is an isoscalar momentum-dependent interaction (eMDYI) in which the isoscalar part of the single nucleon potential is momentum dependent but the isovector part of the single nucleon potential is momentum independent. We note that the MDI interaction is realistic, while the other two are only used as references in order to explore effects of the isospin and momentum dependence of the nuclear interaction.

2. Theoretical models

2.1. MDI interaction

In the isospin and momentum-dependent MDI interaction, the potential energy density $V_{\text{MDI}}(\rho, T, \delta)$ of a thermally equilibrated asymmetric nuclear matter at total

density ρ , temperature T and isospin asymmetry δ is expressed as follows^{28,25},

$$V_{\text{MDI}}(\rho, T, \delta) = \frac{A_u \rho_n \rho_p}{\rho_0} + \frac{A_l}{2\rho_0}(\rho_n^2 + \rho_p^2) + \frac{B}{\sigma + 1} \frac{\rho^{\sigma+1}}{\rho_0^\sigma} (1 - x\delta^2) + \frac{1}{\rho_0} \sum_{\tau, \tau'} C_{\tau, \tau'} \int \int d^3 p d^3 p' \frac{f_\tau(\vec{r}, \vec{p}) f_{\tau'}(\vec{r}, \vec{p}')}{1 + (\vec{p} - \vec{p}')^2 / \Lambda^2}. \quad (1)$$

In the mean field approximation, Eq. (1) leads to the following single particle potential for a nucleon with momentum \vec{p} and isospin τ in the thermally equilibrated asymmetric nuclear matter^{28,25}

$$U_{\text{MDI}}(\rho, T, \delta, \vec{p}, \tau) = A_u(x) \frac{\rho_{-\tau}}{\rho_0} + A_l(x) \frac{\rho_\tau}{\rho_0} + B \left(\frac{\rho}{\rho_0} \right)^\sigma \times (1 - x\delta^2) - 8\tau x \frac{B}{\sigma + 1} \frac{\rho^{\sigma-1}}{\rho_0^\sigma} \delta \rho_{-\tau} + \frac{2C_{\tau, \tau}}{\rho_0} \int d^3 p' \frac{f_\tau(\vec{r}, \vec{p}')}{1 + (\vec{p} - \vec{p}')^2 / \Lambda^2} + \frac{2C_{\tau, -\tau}}{\rho_0} \int d^3 p' \frac{f_{-\tau}(\vec{r}, \vec{p}')}{1 + (\vec{p} - \vec{p}')^2 / \Lambda^2}. \quad (2)$$

In the above the isospin τ is $1/2$ for neutrons and $-1/2$ for protons, and $f_\tau(\vec{r}, \vec{p})$ is the phase space distribution function at coordinate \vec{r} and momentum \vec{p} . The detailed values of the parameters σ , $A_u(x)$, $A_l(x)$, B , $C_{\tau, \tau}$, $C_{\tau, -\tau}$ and Λ can be found in Ref. 28,25 and have been assumed to be temperature independent here. The isospin and momentum-dependent MDI interaction gives the binding energy per nucleon of -16 MeV, incompressibility $K_0 = 211$ MeV and the symmetry energy of 31.6 MeV for cold symmetric nuclear matter at saturation density $\rho_0 = 0.16 \text{ fm}^{-3}$ ²⁸. The different x values in the MDI interaction are introduced to vary the density dependence of the nuclear symmetry energy while keeping other properties of the nuclear equation of state fixed²⁵. We note that the MDI interaction has been extensively used in the transport model for studying isospin effects in intermediate-energy heavy-ion collisions induced by neutron-rich nuclei^{29,30,25,26,31,32,33,34,35}. In particular, the isospin diffusion data from NSCL/MSU have constrained the value of x to be between 0 and -1 for nuclear matter densities less than about $1.2\rho_0$ ^{25,26}. We will thus in the present work consider the two values of $x = 0$ and $x = -1$ with $x = 0$ giving a softer symmetry energy while $x = -1$ giving a stiffer symmetry energy. The potential part of the symmetry energy $E_{\text{sym}}^{\text{pot}}(\rho, x)$ at zero temperature can be parameterized by²⁵

$$E_{\text{sym}}^{\text{pot}}(\rho, x) = F(x) \frac{\rho}{\rho_0} + [18.6 - F(x)] \left(\frac{\rho}{\rho_0} \right)^{G(x)}, \quad (3)$$

where the values of $F(x)$ and $G(x)$ for different x can be found in Ref. 25.

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2.2. MID interaction

In the momentum-independent MID interaction, the potential energy density $V_{\text{MID}}(\rho, \delta)$ of a thermally equilibrated asymmetric nuclear matter at total density ρ and isospin asymmetry δ can be written as

$$V_{\text{MID}}(\rho, \delta) = \frac{\alpha}{2} \frac{\rho^2}{\rho_0} + \frac{\beta}{1+\gamma} \frac{\rho^{1+\gamma}}{\rho_0^\gamma} + \rho E_{\text{sym}}^{\text{pot}}(\rho, x) \delta^2. \quad (4)$$

The parameters α , β and γ are determined by the incompressibility K_0 of cold symmetric nuclear matter at saturation density ρ_0 as in Ref. ⁹ and K_0 is again set to be 211 MeV as in the MDI interaction. And $E_{\text{sym}}^{\text{pot}}(\rho, x)$ is just same as Eq. (3). So the MID interaction reproduces very well the EOS of isospin-asymmetric nuclear matter with the MDI interaction at zero temperature for both $x = 0$ and $x = -1$. The single nucleon potential in the MID interaction can be directly obtained as

$$U_{\text{MID}}(\rho, \delta, \tau) = \alpha \frac{\rho}{\rho_0} + \beta \left(\frac{\rho}{\rho_0}\right)^\gamma + U^{\text{asy}}(\rho, \delta, \tau), \quad (5)$$

with

$$\begin{aligned} U^{\text{asy}}(\rho, \delta, \tau) = & \left[4F(x) \frac{\rho}{\rho_0} + 4(18.6 - F(x)) \left(\frac{\rho}{\rho_0}\right)^{G(x)} \right] \tau \delta \\ & + (18.6 - F(x))(G(x) - 1) \left(\frac{\rho}{\rho_0}\right)^{G(x)} \delta^2. \end{aligned} \quad (6)$$

2.3. eMDYI interaction

The momentum-dependent part in the MDI interaction is also isospin dependent while the MID interaction is fully momentum independent. In order to see the effect of the momentum dependence of the isovector part of the single nucleon potential (nuclear symmetry potential), we can construct an isoscalar momentum-dependent interaction, called extended MDYI (eMDYI) interaction since it has the same functional form as the well-known MDYI interaction for symmetric nuclear matter ³⁶. In the eMDYI interaction, the potential energy density $V_{\text{eMDYI}}(\rho, T, \delta)$ of a thermally equilibrated asymmetric nuclear matter at total density ρ , temperature T and isospin asymmetry δ is written as

$$\begin{aligned} V_{\text{eMDYI}}(\rho, T, \delta) = & \frac{A}{2} \frac{\rho^2}{\rho_0} + \frac{B}{1+\sigma} \frac{\rho^{1+\sigma}}{\rho_0^\sigma} \\ & + \frac{C}{\rho_0} \int \int d^3p d^3p' \frac{f_0(\vec{r}, \vec{p}) f_0(\vec{r}, \vec{p}')}{1 + (\vec{p} - \vec{p}')^2 / \Lambda^2} + \rho E_{\text{sym}}^{\text{pot}}(\rho, x) \delta^2. \end{aligned} \quad (7)$$

Here $f_0(\vec{r}, \vec{p})$ is the phase space distribution function of *symmetric nuclear matter* at total density ρ and temperature T . Again $E_{\text{sym}}^{\text{pot}}(\rho, x)$ has the same expression as Eq. (3). We set $A = \frac{A_u + A_l}{2}$ and $C = \frac{C_{\tau, -\tau} + C_{\tau, \tau}}{2}$, and B , σ and Λ have the same values as in the MDI interaction, so that the eMDYI interaction also gives the same EOS of asymmetric nuclear matter as the MDI interaction at zero temperature for

both $x = 0$ and $x = -1$. The single nucleon potential in the eMDYI interaction can be obtained as

$$U_{\text{eMDYI}}(\rho, T, \delta, \vec{p}, \tau) = U^0(\rho, T, \vec{p}) + U^{\text{asy}}(\rho, \delta, \tau), \quad (8)$$

where

$$U^0(\rho, T, \vec{p}) = A \frac{\rho}{\rho_0} + B \left(\frac{\rho}{\rho_0} \right)^\sigma + \frac{2C}{\rho_0} \int d^3 p' \frac{f_0(\vec{r}, \vec{p})}{1 + (\vec{p} - \vec{p}')^2 / \Lambda^2} \quad (9)$$

and $U^{\text{asy}}(\rho, \delta, \tau)$ is the same as Eq. (6) which implies that the symmetry potential is identical for the eMDYI and MID interactions. Therefore, in the eMDYI interaction, the isoscalar part of the single nucleon potential is momentum dependent but the nuclear symmetry potential is not.

2.4. Thermodynamic Quantities

At zero temperature, $f_\tau(\vec{r}, \vec{p}) = \frac{2}{h^3} \Theta(p_f(\tau) - p)$ and all the integrals in above expressions can be calculated analytically³⁷, while at a finite temperature T , the phase space distribution function becomes the Fermi distribution

$$f_\tau(\vec{r}, \vec{p}) = \frac{2}{h^3} \frac{1}{\exp\left(\frac{p^2}{2m_\tau} + U_\tau - \mu_\tau\right) + 1}, \quad (10)$$

where μ_τ is the chemical potential of proton or neutron and can be determined from

$$\rho_\tau = \int f_\tau(\vec{r}, \vec{p}) d^3 p. \quad (11)$$

In the above, m_τ is the proton or neutron mass and U_τ is the proton or neutron single nucleon potential in different interactions. From a self-consistency iteration scheme^{36,38}, the chemical potential μ_τ and the distribution function $f_\tau(\vec{r}, \vec{p})$ can be determined numerically.

From the chemical potential μ_τ and the distribution function $f_\tau(\vec{r}, \vec{p})$, the energy per nucleon $E(\rho, T, \delta)$ can be obtained as

$$E(\rho, T, \delta) = \frac{1}{\rho} \left[V(\rho, T, \delta) + \sum_\tau \int d^3 p \frac{p^2}{2m_\tau} f_\tau(\vec{r}, \vec{p}) \right]. \quad (12)$$

Furthermore, we can obtain the entropy per nucleon $S_\tau(\rho, T, \delta)$ as

$$S_\tau(\rho, T, \delta) = -\frac{8\pi}{\rho h^3} \int_0^\infty p^2 [n_\tau \ln n_\tau + (1 - n_\tau) \ln(1 - n_\tau)] dp \quad (13)$$

with the occupation probability

$$n_\tau = \frac{1}{\exp\left(\frac{p^2}{2m_\tau} + U_\tau - \mu_\tau\right) + 1}. \quad (14)$$

Finally, the pressure $P(\rho, T, \delta)$ can be calculated from the thermodynamic relation

$$P(\rho, T, \delta) = \left[T \sum_\tau S_\tau(\rho, T, \delta) - E(\rho, T, \delta) \right] \rho + \sum_\tau \mu_\tau \rho_\tau. \quad (15)$$

3. LG Phase Transition

3.1. Chemical Potential Isobar

With the above theoretical models, we can now study the LG phase transition in hot asymmetric nuclear matter. The phase coexistence is governed by the Gibbs conditions and for the asymmetric nuclear matter two-phase coexistence equations are

$$\mu_i^L(T, \rho^L, \delta^L) = \mu_i^G(T, \rho^G, \delta^G), \quad (i = n \text{ and } p) \quad (16)$$

$$P^L(T, \rho^L, \delta^L) = P^G(T, \rho^G, \delta^G), \quad (17)$$

where L and G stand for liquid phase and gas phase, respectively. The chemical stability condition is given by

$$\left(\frac{\partial \mu_n}{\partial \delta} \right)_{P,T} > 0 \text{ and } \left(\frac{\partial \mu_p}{\partial \delta} \right)_{P,T} < 0. \quad (18)$$

The Gibbs conditions (16) and (17) for phase equilibrium require equal pressures and chemical potentials for two phases with different concentrations and asymmetries. For a fixed pressure, the two solutions thus form the edges of a rectangle in the proton and neutron chemical potential isobars as a function of isospin asymmetry δ and can be found by means of the geometrical construction method^{8,12}.

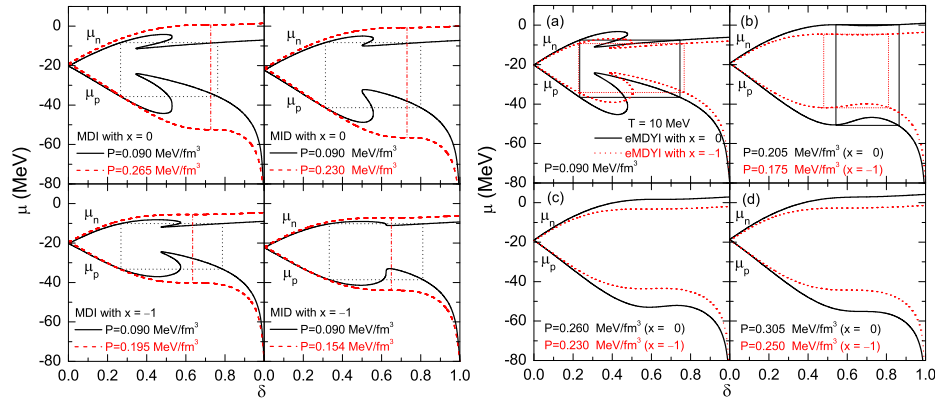


Fig. 1. (Color online) The chemical potential isobar as a function of the isospin asymmetry δ at $T = 10$ MeV for the MDI and MID interactions (left) and the eMDYI interaction (right) with $x = 0$ and $x = -1$. The geometrical construction used to obtain the isospin asymmetries and chemical potentials in the two coexisting phases is also shown. Taken from Ref. ²⁷.

We calculate the chemical potential isobars at $T = 10$ MeV, which is a typical temperature of LG phase transition. The solid curves shown in the left panel of

Fig. 1 are the proton and neutron chemical potential isobars as a function of the isospin asymmetry δ at a fixed temperature $T = 10$ MeV and pressure $P = 0.090$ MeV/fm³ by using the MDI and MID interactions with $x = 0$ and $x = -1$. The resulting rectangles from the geometrical construction are also shown by dotted lines in the left panel of Fig. 1. When the pressure increases and approaches the critical pressure P_C , an inflection point will appear for proton and neutron chemical potential isobars. Above the critical pressure, the chemical potential of neutrons (protons) increases (decreases) monotonically with δ and the chemical instability disappears. In the left panel of Fig. 1, we also show the chemical potential isobar at the critical pressure by the dashed curves. At the critical pressure, the rectangle is degenerated to a line vertical to the δ axis as shown by dash-dotted lines. The values of the critical pressure are 0.265, 0.230, 0.195 and 0.154 MeV/fm³ for the MDI interaction with $x = 0$, MID interaction with $x = 0$, MDI interaction with $x = -1$ and MID interaction with $x = -1$, respectively.

Shown in the right panel of Fig. 1 is the chemical potential isobar as a function of the isospin asymmetry δ at $T = 10$ MeV by using the eMDYI interaction with $x = 0$ and $x = -1$. Compared with the results from the MDI and MID interactions, the main difference is that the left (and right) extrema of μ_n and μ_p do not correspond to the same δ but they do for the MDI and MID interactions as shown in the left panel. The chemical potential of neutrons increases more rapidly with pressure than that of protons in this temperature. At lower pressures, for example, $P = 0.090$ MeV/fm³ as shown in Panel (a), the rectangle can be accurately constructed and thus the Gibbs conditions (16) and (17) have two solutions. Due to the asynchronous variation of μ_n and μ_p with pressure, we will get a limiting pressure P_{lim} above which no rectangle can be constructed and the coexistence equations (16) and (17) have no solution. Panel (b) shows the case at the limiting pressure with $P_{\text{lim}} = 0.205$ and 0.175 MeV/fm³ for $x = 0$ and $x = -1$, respectively. With increasing pressure, in Panel (c) μ_n passes through an inflection point while μ_p still has a chemically unstable region, and in Panel (d) μ_p passes through an inflection point while μ_n increases monotonically with δ .

3.2. Binodal surface

For each interaction, the two different values of δ correspond to two different phases with different densities and the lower density phase (with larger δ value) defines a gas phase while the higher density phase (with smaller δ value) defines a liquid phase. Collecting all such pairs of $\delta(T, P)$ and $\delta'(T, P)$ thus forms the binodal surface.

In Fig. 2 (a), we show the section of the binodal surface at $T = 10$ MeV for the MDI and MID interactions with $x = 0$ and $x = -1$. On the left side of the binodal surface there only exists a liquid phase and on the right side only a gas phase exists. In the region of “filet mignon” is the coexistence phase of liquid phase and gas phase. Interestingly, we can see from Fig. 2 (a) that the stiffer symmetry energy ($x = -1$)

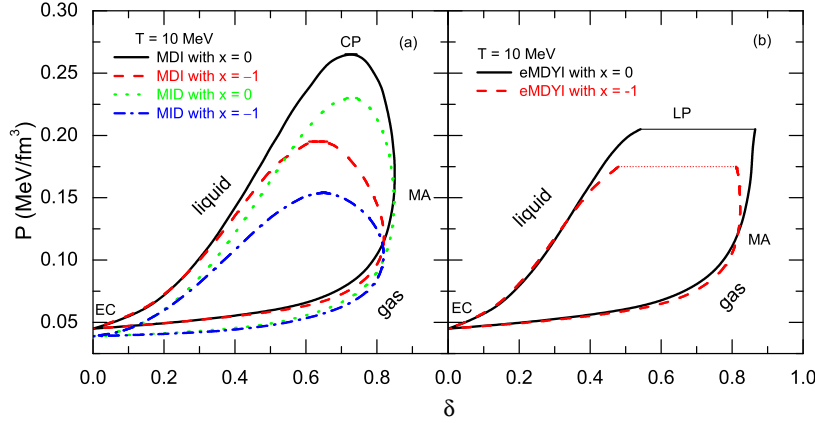


Fig. 2. (Color online) (a) The section of binodal surface at $T = 10$ MeV in the MDI and MID interactions with $x = 0$ and $x = -1$. The critical point (CP), the points of equal concentration (EC) and maximal asymmetry (MA) are also indicated. (b) The section of binodal surface at $T = 10$ MeV in the eMDYI interaction with $x = 0$ and $x = -1$. LP represents the limiting pressure. Taken from Ref. ²⁷.

significantly lowers the critical point (CP) and makes the maximal asymmetry (MA) a little smaller. Meanwhile, the momentum dependence in the interaction (MDI) lifts the CP in a larger amount, while it seems to have no effects on the MA point. In addition, just as expected, the value of x does not affect the equal concentration (EC) point while the momentum dependence lifts it slightly (by about $0.005 \text{ MeV}/\text{fm}^3$). These features clearly indicate that the critical pressure and the area of phase-coexistence region in hot asymmetric nuclear matter is very sensitive to the stiffness of the symmetry energy with a softer symmetry energy giving a higher critical pressure and a larger area of phase-coexistence region. Meanwhile, the critical pressure and the area of phase-coexistence region are also sensitive to the momentum dependence. The MDI interaction has a larger area of phase coexistence region and a larger value of the critical pressure, compared to the result of MID interaction in the temperature of $T = 10$ MeV.

Fig. 2 (b) displays the section of the binodal surface at $T = 10$ MeV by using the eMDYI interaction with $x = 0$ and $x = -1$. We can see that the curve is cut off at the limiting pressure with $P_{\text{lim}} = 0.205$ and $0.175 \text{ MeV}/\text{fm}^3$ for $x = 0$ and $x = -1$, respectively. We can also see that the limiting pressure and the area of phase-coexistence region are still sensitive to the stiffness of the symmetry energy with a softer symmetry energy ($x = 0$) giving a higher limit pressure and a larger area of phase-coexistence region in this temperature.

Comparing the results of the MDI and MID interactions shown in Fig. 2 (a),

we can see that for pressures lower than the limiting pressure, the binodal surface from the eMDYI interaction is similar to that from the MDI interaction. This feature implies that the momentum dependence of the symmetry potential has little influence on the LG phase transition in hot asymmetric nuclear matter while the momentum dependence of the isoscalar single nucleon potential significantly changes the area of phase-coexistence region for pressures lower than the limiting pressure. For pressures above the limiting pressure, the momentum dependence of both the isoscalar and isovector single nucleon potentials becomes important.

4. Summary

In summary, we have studied the liquid-gas phase transition in hot neutron-rich nuclear matter within a self-consistent thermal model using three different nuclear effective interactions, namely, the isospin and momentum dependent MDI interaction constrained by the isospin diffusion data in heavy-ion collisions, the momentum-independent MID interaction, and the isoscalar momentum-dependent eMDYI interaction. At zero temperature, the above three interactions give the same EOS for asymmetric nuclear matter. By analyzing liquid-gas phase transition in hot neutron-rich nuclear matter with the above three interactions, we find that the boundary of the phase-coexistence region is very sensitive to the density dependence of the nuclear symmetry energy. A softer symmetry energy leads to a higher critical pressure and a larger area of the phase-coexistence region. In addition, the area of phase-coexistence region are also seen to be sensitive to the isospin and momentum dependence of the nuclear interaction. For the isoscalar momentum-dependent eMDYI interaction, a limiting pressure above which the liquid-gas phase transition cannot take place has been found.

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